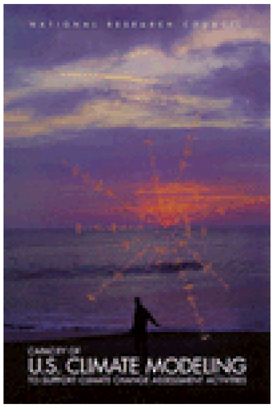

Capacity of U.S. Climate Modeling to Support Climate Change Assessment Activities

Climate Research Committee, National Research Council

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Climate Research Committee
Board on Atmospheric Sciences and Climate
Commission on Geosciences, Environment, and Resources
National Research Council

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Preface

This report responds to an oral request by two U.S. Global Change Research Program (USGCRP) agency program managers, Michael Hall of NOAA and Jay Fein of NSF, made at the Climate Research Committee (CRC) meeting held on October 15-17, 1997, and as part of an understanding with Mike MacCracken of the USGCRP Program Office. In June 1996, the CRC and the USGCRP co-hosted a forum on the status and infrastructure needs of climate modeling in the United States. Prior to the forum, public discussion on the organization of the U.S. climate modeling community and the adequacy of resources available to it had been spurred by four prominent climate research scientists in an open letter (October 1995) to USGCRP principals and widely circulated to the climate research community (See Appendix A). In this letter they asserted that the "American [climate modeling] effort is falling seriously behind that of Europe and, perhaps, Japan," and expressed concern that the United States was in danger of being "relegated to permanent second-class status in this critical area of Earth science research." They went on to outline three strategic options for regaining the lead in global climate modeling. The issues raised in this letter remain largely unresolved and, subsequently, other related issues have also been raised. In particular, some have questioned the adequacy of the present organization of the U.S. climate modeling community to respond to the challenge of participation in the work of the Intergovernmental Panel on Climate Change (IPCC), as well as the sufficiency of computer facilities available within the United States to serve this purpose.

This report is intended to inform USGCRP agencies on issues related to the capability of U.S. climate modeling efforts to support national and international climate assessments, and the sufficiency of computational resources available for this purpose. In this report, the committee will address three specific questions:

1. Do USGCRP agencies have a coordinated approach for prioritizing from a national perspective their climate modeling research and assessment efforts?
2. Are resources allocated effectively to address such priorities?
3. How can the U.S. climate modeling community make more efficient use of its available resources?

The Climate Research Committee hopes that federal agencies and the USGCRP will find this report useful as they work to enhance the contribution that the U.S. climate research community can make to national and international assessments of climate change.

THOMAS KARL, CHAIR

Acknowledgment of Reviewers

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the NRC in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

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While the individuals listed above have provided many constructive comments and suggestions, responsibility for the final content of this report rests solely with the authoring committee and the NRC.

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Executive Summary

The U.S. government has pending before it the ratification of the Kyoto Protocol, an agreement to limit the emissions of greenhouse gases (GHGs), which is largely based on the threat GHGs pose to the global climate. Such an agreement would have significant economic and national security implications, and therefore any national policy decisions regarding this issue should rely in part on the best possible suite of scenarios from climate models.

The U.S. climate modeling research community is a world leader in intermediate and smaller[1] climate modeling efforts—research that has been instrumental in improving the understanding of specific components of the climate system. Somewhat in contrast, the United States has been less prominent in producing high-end climate modeling results, which have been featured in recent international assessments of the impacts of climate change. The fact that U.S. contributions of these state-of-the-art results have been relatively sparse has prompted a number of prominent climate researchers to question the current

[1] An example of what is referred to in this document as a small modeling effort is one using a global, stand-alone atmospheric climate model at R15 (~4.5°×7.5°) resolution; an example of an intermediate effort is one using a global, stand-alone atmospheric climate model at T42 (2.8°×2.8°) resolution; an example of a large or high-end modeling effort is one using a global, coupled T42 atmospheric / 2°×2° oceanic model (or finer resolution) for centennial-scale simulations of transient climate change.

organization and support of climate modeling research in the United States, and has led ultimately to this report.

In this evaluation of U.S. climate modeling efforts, the Climate Research Committee (CRC) was asked by USGCRP agency program managers to address three key questions, which form the basis for the NRC Statement of Task (Appendix B) for this report:

1. Do USGCRP agencies have a coordinated approach for prioritizing from a national perspective their climate modeling research and assessment efforts?
2. Are resources allocated effectively to address such priorities? A related question that the report addresses is whether currently available resources in the United States are adequate for the purpose of high-end climate modeling.
3. How can the U.S. climate modeling community make more efficient use of its available resources?

• Regarding the first question—**the CRC has reached the conclusion that, although individual federal agencies may have established well-defined priorities for climate modeling research, there is no integrated national strategy** designed to encourage climate modeling that specifically addresses, for example, the objectives of the USGCRP, the needs for comprehensive contributions to the IPCC science base, and the priorities developed by the CRC in its chapter in the Board on Atmospheric Sciences and Climate's report, *Atmospheric Sciences Entering the Twenty-First Century* (NRC, 1998a). We suggest that the science-driven climate modeling agenda, which has been largely shaped by individual investigators, has been reasonably effective in advancing the frontiers of science, but has not been adequately responsive to the immediate needs of the broader community (e.g., the “impacts” and “policy” communities).

• With respect to the second question—**we find that, compared with intermediate and smaller modeling efforts, insufficient human and computational resources are being devoted to high-end, computer-intensive, comprehensive modeling, perhaps in**

• **part because of the absence of a nationally coordinated modeling strategy.** Consequently, in contrast to some of the foreign modeling centers, U.S. modeling centers have found it difficult to perform coupled atmosphere-ocean climate change scenario simulations at the spatial resolutions relevant to certain national policy decisions (e.g., finer than 500 km × 800 km). The recognized strengths of U.S. intermediate modeling capabilities (see, e.g., the sizable contributions from the U.S. coarse-resolution climate modeling efforts in the IPCC reports) have not been effectively harnessed in the development of high-end, U.S.-based models. For instance, leading Earth system modeling efforts in the United States suffer from a computationally limited ability to test and run models in a timely fashion. The ability of the climate community to acquire state-of-the-art mainframes is severely hampered by a Department of Commerce "antidumping order" prescribing a financial penalty in excess of 400 percent on the purchase price of the world's most powerful commercial supercomputers, which are Japanese in origin. The climate community has not been provided with the financial or computational resources to overcome this barrier and has, therefore, been unable to fully capitalize on the scientific potential within the United States. Not only is insufficient access to powerful computers hampering scientific progress in understanding fundamental climate processes, it is also limiting the ability to perform simulations of direct relevance to policy decisions related to human influences on climate. However, *at least as important* as the insufficiency of computing resources are the lack of national coordination and insufficient funding of human resources.

• Regarding the third question—the CRC finds that:

1. **A set of national goals and objectives that are agreed to by the USGCRP agencies is essential.**
2. **A concerted effort by the relevant agencies is needed to establish a coordinated national strategy for climate modeling.**
3. **In order to optimally use existing scientific capabilities, adequate resources, including greatly improved**

supercomputing capabilities, need to be provided to the climate modeling community.

4. **The reliance of the United States upon other countries for high-end climate modeling must be redressed.**

In order to avoid the aforementioned problem regarding priority setting, the USGCRP could assume increased responsibility for identifying, from an interagency perspective, any gaps or imbalances in the research priorities established by the individual agencies. At present, however, this is made difficult because some agencies have excluded from their USGCRP budgets the computational and human resources to support comprehensive, coupled atmosphere-ocean climate modeling efforts on a par with those in several foreign countries. **Although an entirely top-down management approach for climate modeling is viewed as undesirable, national economic and security interests nevertheless require a more comprehensive national strategy for setting priorities, and improving and applying climate models.** An effective national approach to climate modeling should ensure that available resources are allocated appropriately according to agreed upon science research and societal priorities and are efficiently utilized by the modeling community. We acknowledge that justification for and design of such a strategy would require a more complete evaluation of the current status of climate modeling in the United States than was possible in developing this report. Development of such a strategy should take place with full involvement of climate modelers within academia and the national climate research centers, along with users of climate modeling results and agency program managers.

Climate modeling in the United States promotes a healthy competition among various groups, but without better coordination of research among national laboratories and between them and the academic community, it may be difficult to optimally utilize available human and high-end computer resources. In particular, standardization of model output, model evaluation tools, and modular programming structures can facilitate model development and minimize duplication of effort, with the possibility that prudent standardization may yield some cost savings. High-end modeling coordination could also be enhanced through refereed workshops to discuss the pertinent scientific and associated societal issues and to recommend priorities. Effective collaborative linkages between process studies and modeling groups should also be encouraged to facilitate the difficult task of developing, implementing, and testing new model parameterizations. In addition, increased coordination of research-based and operational modeling activities will help ensure that expertise in these two communities is shared. These are but a few of the types of coordinating activities that should be vigorously and consistently pursued.

The CRC finds that the United States lags behind other countries in its ability to model long-term climate change. Those deficiencies limit the ability of the United States:

1. to predict future climate states and thus:

a) assess the national and international value and impact of climate change;
b) formulate policies that will be consistent with national objectives and be compatible with global commitments;

2. to most effectively advance understanding of the underlying scientific issues pertaining to climate variability and change.

Although collaboration and free and open information and data exchange with foreign modeling centers are critical, it is inappropriate for the United States to rely heavily upon foreign centers to provide high-end modeling capabilities. There are a number of reasons for this, including the following:

1. U.S. scientists do not necessarily have full, open, and timely access to output from European models, particularly as the commercial value of these predictions and scenarios increases in the future.[2]
2. Decisions that might substantially affect the U.S. economy might be made based upon considerations of simulations (e.g., nestedgrid runs) produced by countries with different priorities than those of the United States.

[2] U.S. researchers, however, do currently have access to output from most simulations of transient climate change produced by foreign models.

3. If U.S. scientists lose involvement in high-end modeling activities, they may miss opportunities to gain valuable insights into the underlying processes that are critical to subsequent modeling investigations. In this regard the issue of accessibility is much more than just a commercial and political issue; in order to most effectively advance the science in the United States, researchers need to have access to both model output and the models themselves to iteratively diagnose the output, advance knowledge of climate, and improve the models' predictive capabilities.
4. There are currently relatively few modeling centers anywhere in the world capable of producing moderate resolution (e.g., 250–300 km grid spacing), transient climate simulations. The differences in simulated climate produced by each of these models' different structures help to bound the range of outcomes that the climate system might produce given a certain forcing scenario. Thus, the state of climate modeling throughout the world is such that the addition or removal of even a single model could affect the confidence levels assigned to certain scenarios of future climate change. In other words, not only would the United States benefit from enhancements in its modeling capabilities, the international community would benefit from these efforts as well. The marginal benefits from only modestly increased investments in comprehensive models in the United States could be very large, because, if properly coordinated, the enhanced emphasis on high-end modeling could be built upon the excellent existing U.S. strength in small and intermediate modeling.

Thus, to facilitate future climate assessments, climate treaty negotiations, and our understanding and predictions of climate, it is appropriate to develop a national climate modeling strategy that includes the provision of adequate computational and human resources and is integrated across agencies.

Capacity of U.S. Climate Modeling

BACKGROUND

In October of 1995 four U.S. climate researchers raised concerns in a letter (see Appendix A) to the USGCRP agency managers that the U.S. position of leadership in the development, improvement, and application of climate models had eroded. They offered various options for progress in these areas, emphasizing a well-coordinated, distributed national climate modeling program. While the specific recommendations of that letter are somewhat different than those of this report, the letter was one of the primary impetuses for the Climate Research Committee (CRC) of the National Research Council (NRC) and the USGCRP Program Office to hold a jointly sponsored forum on the "Quality and Infrastructure of Climate Modeling in the United States" on 11–12 June 1996 (see Appendix C, which contains the invitation letter to the forum and the agenda). About 70 scientists and federal program managers participated. In preparation for the forum, the USGCRP Program Office distributed a questionnaire to over 100 members of the climate-modeling community for their written comments on "the strengths and weaknesses of the present research and applications, related activities, and infrastructure for decadal-centennial scale climate modeling in the United States," and received about 25 responses. Some of the findings in this report are based in part on the discussions at the forum and in answers to the questionnaire.

POLICY CONTEXT.

The U.S. government has pending before it the ratification of the Kyoto Protocol, an agreement to limit the emissions of greenhouse gases (GHGs), which is largely based on the threat GHGs pose to the global climate. Such an agreement would have significant economic and national security implications, and therefore any national policy decisions regarding this issue should rely in part on the best possible suite of scenarios from climate models.

This Protocol relating to GHGs is only one of a series of policy issues under consideration that involve climate and climate change. The Intergovernmental Panel on Climate Change (IPCC, 1998) lists several major areas of concern where climate changes would have a critical impact on policy decisions: ecosystems, hydrology and water resources, food and fiber production, coastal systems, human settlements, and human health. Governments, corporations, and the public are faced with a multitude of decisions in each one of these fundamental areas of concern. In terms of the daily lives of individuals, these decisions impact on jobs, food, economic well-being, livable environments, and general prosperity.

Issues bearing on the formulation of local, national, or global climate change policies are complex, and not always well defined. It could be just as disastrous to impose unnecessary restraints on society out of ignorance as it is to fail to act in time from indecision. Human, political, economic, and scientific considerations all come into play. These considerations can be at odds with each other in fundamental ways. Compromise rooted in knowledge is essential if progress is to be made.

Policy makers must have solid, credible information to define the issues, to generate realistic compromises, and to move the policy debates and decision processes forward. It is essential to provide the capability to produce well founded forecasts of the magnitudes and trends in climate change, as well as to identify the causative factors—natural and anthropogenic. At the core of creating that capability is the use of climate system models. These models, which may incorporate components including atmospheric, oceanic, and terrestrial dynamics, radiative characteristics, and chemistry, provide the only quantitative mechanism by which climate projections can be put in a context suitable for policy assessment and decisions.

CURRENT SMALL AND INTERMEDIATE MODELING CAPABILITIES

The U.S. climate modeling community excels in conceiving and carrying out process and diagnostic studies that form the basis for climate model improvement. Likewise, the intermediate climate modeling research efforts, which a few years ago may have been referred to as high-end (see footnote 1), have been appropriately encouraged and supported. Evidence of this work are the coupled modeling contributions by the United States to the IPCC process, as well as the development of some of the leading mesoscale models (e.g., MM5, ETA, and COAMPS).[3] U.S. leadership in this area has involved, for example, sensitivity studies, exploration of new hypotheses, and studies aimed at quantifying and understanding model uncertainties.

The relatively successful forecasts of the regional climate anomalies associated with the 1997–1998 ENSO event (COLA, 1998) and adaptations that were made in response to these forecasts, highlight the societal value of climate forecasting.[4] The benefits that are being experienced as a result of this capability, underscore the potential utility of the development of long-term climate change scenarios, in particular, because future, long-term, anthropogenic

[3] In highlighting the U.S. intermediate-level modeling expertise, it should not be overlooked that several foreign, intermediate modeling efforts, such as those of the ECMWF in weather forecasting, are at the cutting edge, sometimes leading those of the United States.

[4] The computational requirements of these models, especially for operational production of ensembles of simulations, are enormously large, and the United States is at a competitive disadvantage, in this regard, compared to the major European modeling centers because of the greater access to appropriate computational resources outside the United States.

climate changes are likely to be larger than those that currently occur on the seasonal-to-interannual time frame of the ENSO phenomenon.

CURRENT HIGH-END MODELING CAPABILITIES AND NEEDS

Some of the earliest and defining climate change simulations and sensitivity experiments were carried out in the United States, and the contributions from the U.S. modeling community were essential to the overall understanding of various climate issues. That initial productivity has been difficult to sustain because of a lack of coordination and availability of the requisite computational and human resources.[5] This may explain in part why, in contrast to some of the foreign modeling centers, U.S. modeling centers have found it difficult to perform coupled atmosphere-ocean climate change scenario simulations at the spatial resolutions (e.g., finer than 500 km × 800 km) of direct relevance to national policy actions presently being considered to mitigate future global change. According to discussions at the forum, at least some in the scientific community expressed the concern that the United States should have been able to contribute more in terms of high-end, coupled-model GHG and aerosol simulations to the recent IPCC assessment.

The computational capabilities that are required to incorporate various spatial resolutions in climate models are outlined in Table 1. It is apparent from Table 1 that several foreign modeling centers currently possess greater computing power than that of the U.S. centers. However, no modeling center currently has the computational ability to realistically depict small-scale/high-impact atmospheric processes in multi-century, transient simulations — the type of simulation required to reduce uncertainties associated with assessments of the societal implications of climate change. Simulation of certain atmospheric features such as mesoscale convective complexes and hurricanes, even in a rudimentary fashion, requires a model spatial resolution of 10 km or less, which, in turn, requires

[5] The view, repeatedly expressed at the forum, was that U.S. climate modeling research is at the forefront in most respects, but not all.

Table 1. Computational capabilities at some of the major climate modeling centers

Date	**Comput. Speed**[A] (GFLOPS)	**System**[B] / No. of Processors	**Approx. Run Time**[C]	**Horiz. Resolution (Km^2)**[D] / Vertical Levels Atmosphere	Ocean	**Modeling Group**
1998	1	Cray J90 / 16	3 days	500×830 / 18	_[E]	e.g., PSU
1998	2.6	Origin 2000 / 64 (four)	3 days	310×310 / 18	65×65 / 20	DOE
1998	5	Cray C90 / 16	2.5 days	310×310 / 18	≥130×270 / 45	NCAR
1998	15	Cray T932 / 26	5 hours	250×420 / 14	190×80 / 18	GFDL
1998	35	Cray T3E / 696	**[F]	280×420 / 19	140×140 / 20	HC
1998	20–25	NEC SX-4/32	1.5 days	310×310 / 17	220 × 55 / 25	ABOM
1998	20–25	NEC SX-4/32	3 days	280×280 / 32	200×200 / 29	CCCMA
1998	75	Fujitsu VPP / 116	14 days	200×200 / 31	56×56 / 20	ECMWF[G]
2000	1000	Currently unspecified	8 hours	140×140 / 18	30×30 / 20	ACPI
2001	10000	Currently unspecified	8 hours	70×70 / 18	15×15 / 20	ACPI
2003	40000	Currently unspecified	8 hours	30×30 / 18	9×9 / 20	ACPI

PSU = Penn State Earth System Science Center; NCAR = National Center for Atmospheric Research; GFDL = Geophysical Fluid Dynamics Laboratory; HC = Hadley Center, U.K.; ABOM = Australian Bureau of Meteorology Research Centre; CCCMA = Canadian Center for Climate Modeling and Analysis; ECMWF = European Center for Medium-Range Weather Forecasting; DOE = Department of Energy, Los Alamos; ACPI = Accelerated Climate Prediction Initiative

Individuals who supplied information for this table include David Anderson, David Bader, Bill Buzbee, Robert Malone, William Peterson, Ronald Stouffer, Vince Wayland, Francis Zwiers, and members of the CRC.

[A] GFLOPS = 10^9 floating point operations per second (typical sustained)

[B] The highest performance machine at each institution.

[C] Run time is a rough approximation of the wallclock time needed to simulate 15 model years on a dedicated computer, *assuming optimal multi-tasking* (e.g., running as many separate simulations as can be accommodated by all of the machine's processors and dividing the final wallclock time by the number of simulations).

[E] —= This climate system component is not included in this particular type of model run.

[F] **= Not available

[G] The ECMWF model is designed for operational forecasting, not multi-decadal climate scenario analysis, like the other models in this table. It is included to illustrate the large computational capability that has been devoted to this activity abroad.

computational throughput more than three orders of magnitude greater than is presently available to U.S. climate modelers. This is at the upper range of the 40 teraflop (10^{12} floating point operations per second) capability proposed by the Advanced Climate Prediction Initiative (ACPI, 1998) for the year 2003.[6]

Current model deficiencies are not only in the realm of spatial, but also temporal resolution. For example, the current GFDL coupled model is generally run without a diurnal cycle, thereby precluding the ability to explicitly resolve critical variables such as daily maximum and minimum temperatures. The United States possesses the intellectual ability to put together models capable of better resolving many of these important climatic features. However, the current lack of coordinated computational capability limits the ability of U.S. scientists to develop such policy-relevant scenarios; it also limits the ability of U.S. scientists to diagnose and understand the physics of climate and climate change.

Currently, there are relatively few modeling centers anywhere in the world capable of producing relatively high-resolution (e.g., 250–300 km grid spacing), transient climate simulations. The differences in simulated climate produced by the various structures and compositions of these few models help to bound the range of outcomes that the climate system might produce given a certain forcing scenario. Thus, the state of climate modeling throughout the world is such that the addition or removal of even a single model could affect the confidence levels assigned to certain scenarios of future climate change. In other words, not only would the United States benefit from enhancements in its modeling capabilities but the international community would benefit as well.

In addition to the need for simulations produced by different climate models, estimates also need to be produced of the stochastic nature of climate change within a given model, i.e., ensembles of simulations, using slightly different initial conditions. Ideally, a new ensemble should be produced whenever significant improvements in a

[6] The ACPI is an unfunded Department of Energy plan for increasing U.S. computing power for climate applications. The system and number of processors are currently unspecified.

model's code become available. The production of such ensembles to perform model diagnostics and climate change assessments in a timely fashion requires high computational throughput. Further increasing computational requirements is the use of regional, high-resolution models nested within medium-to-coarse resolution, global coupled models. U.S. climate modeling centers currently do not possess the computational resources required for these types of simulations.

While trying to catch up with foreign, high-end modeling efforts, the necessity of adequate model testing should not be overlooked. Testing, diagnosis, and documentation of model characteristics must be an intrinsic part of the procedure for developing climate change scenarios for assessment purposes. Again, the computational and human resources for this facet are substantial and are not sufficiently available to U.S. climate modelers.

ACCESS TO FOREIGN MODEL OUTPUT

A further hindrance to the sub-optimal high-end U.S. modeling capabilities is that the United States is not assured full, open, and timely access to output from foreign models. Ready access to foreign model output could alleviate some of the need for high-end domestic capabilities. It is acknowledged that in many instances the output from foreign models is readily forthcoming, such as in the case of the Atmospheric and Coupled Model Intercomparison Projects (AMIP/CMIP), the LINK project at the U.K. Climatic Research Unit, as well as countless other formal and informal data transmittals. However, the committee is concerned that access to foreign model output is not guaranteed. In several recent instances, access to foreign atmospheric data has either been denied or only occurred at considerable expense to U.S. entities (see Appendix D). As the commercial value of these data becomes more apparent, the possibility of greater restrictions exists, particularly with the movement towards privatization of meteorological agencies.

This issue of data accessibility is important for at least two reasons, and ultimately points towards the need for a high level of domestic Earth system modeling capability. First, if political decisions are to be based upon the most current and reliable information, access to those data must be ensured. The NRC Pathways report (NRC, 1998b) addressed this in its statement that "*the USGCRP must foster the development and application of models at the scale of time and space needed to understand and project the specific mechanisms controlling changes in the state of the Earth system thus providing the information required to support important policy processes.*" Second, because the commercial value of data is in part a function of its timeliness, potential commercial opportunities may be lost if prompt access to climate model data is not guaranteed. These needs can be met by furthering the development, running, and testing of high-end models within the United States.

A further point is that the more difficult it is to access a model and its output, the more opaque are the model's results. If the United States is to fully capitalize upon the most recent model products, it must have researchers directly involved in the modeling process who understand the details of a given model's underpinnings so that they can be in a position to comprehend and interpret nuances of that model's simulations. If U.S. scientists are not directly involved in the high-end modeling itself, they may miss opportunities to gain valuable insights into the underlying processes that are critical to subsequent modeling investigations. In this regard the issue of accessibility is much more than just a commercial and political issue; in order to most effectively advance the science in the United States, researchers need to have access to both model output and the models to iteratively diagnose the output, advance our knowledge of climate, and improve the model's predictive capabilities. To some extent this can be addressed by enhancing collaborations with foreign climate modeling groups, but ultimately this can go only so far.

The concerns regarding the need for U.S. high-end modeling capabilities are also based, in part, on the possibility that decisions that might substantially affect the U.S. economy might be founded upon considerations of simulations produced by countries with different priorities than those of the United States. While the leading climate models are global in scale, their ability to represent small-scale, regionally dependent processes (e.g., hurricanes and extreme flooding events) can currently only be depicted in them using high-resolution, nested grids. It is reasonable to assume that foreign modeling centers will implement such nested grids to most realistically simulate processes on domains over their respective countries which may not focus on or even include the United States.

PRIORITY SETTING

The information gathered from active climate researchers and agency program managers at the CRC/USGCRP modeling forum indicated that climate modeling priorities are established primarily within individual agencies, specifically, DOE, NASA, NOAA, and NSF. Individual agency program managers appear to be aware of modeling activities in other agencies through informal personal exchanges of information and through the USGCRP Integrated Modeling and Prediction Working Group (IMAP) (No analogous coordinating activity involving the directors of U.S. climate modeling centers exists.). Although these limited harmonization efforts may provide some context for setting funding priorities, we conclude that research funding decisions are mainly driven by the missions of the individual agencies without strong interagency coordination.

U.S. funding agencies rely heavily on working scientists to shape the climate modeling program. This system promotes a healthy competition among modeling groups and has given rise to a rich diversity of climate modeling efforts that is highly valued by the scientific community. This system, however, does not necessarily promote research that addresses the questions of most importance to policy makers or U.S. society at large, particularly if no agency considers a given issue to be among its priorities.

The approach that has been used in the United States to set research priorities for climate modeling can be contrasted with some European countries, especially the United Kingdom and Germany, where a stronger top-down management approach is used for setting research priorities. These countries, which have smaller GDPs than the United States, have leveraged their funding of research to more directly serve policy needs (at the partial expense of fundamental climate research). To facilitate progress, the United States should establish a set of priorities that carefully balances both policy and science needs and avoids a top-down prioritization of research activities driven by short-term agency agendas that might ultimately dissipate scientific resources.

COORDINATION

The lack of national coordination and funding, and thus sustained interest, are substantial reasons why the United States is no longer in the lead in high-end climate modeling.[7] Many scientists at the time of the forum believed that the current major U.S. modeling centers were not adequately responding to the challenges of integrating component models of the atmosphere, oceans, land surface, and atmospheric chemistry, that are needed for climate change scenario studies. At that time, some members of the academic community averred that their expertise was not being effectively utilized in the development of these comprehensive models. Moreover, the coordination of model development activities seemed to be fragmented even within the major climate modeling centers.

The USGCRP could assume increased responsibility for identifying, from an interagency perspective, any gaps or imbalances in the research priorities established by the individual agencies. The USGCRP is, however, limited in this area because some agencies have excluded from their USGCRP budgets the computational and human resources allocated to support some major U.S. climate modeling efforts. Although ideally any imbalances identified should be rectified, it appears that the USGCRP does not currently have the means to ensure this. Thus, this may be a fundamental weakness of the current approach to setting climate modeling priorities.

[7] This view is supported by Finding 6 of NRC (1998b): "*Advances in developing and most importantly in testing and evaluating models are needed.* ***The United States is no longer in the lead in this critical field.***"

As in setting priorities, the establishment of a coordinated modeling strategy in the United States should carefully balance both policy and science needs. The implementation of these priorities should not come at the expense of small and intermediate modeling, which currently form a solid base of expertise in the United States. Although better coordination of U.S. climate modeling activities is advocated and is likely to lead to substantial enhancements in overall capabilities, coordination alone is not sufficient. U.S. modelers cannot produce the high-resolution, multi-decade, ensemble simulations necessary to perform detailed assessments of anthropogenic climate change without an increase in the computational capability available to U.S. scientists.

With the development of coupled models, including the atmosphere, oceans, and biosphere, there are common problems that must be addressed by the overall model framework that links the components of the system. It is possible that movement towards increased modularity among model components and a common component interface, sometimes referred to as a "flux coupler," might speed improvement of these comprehensive climate models. In principle, independently developed individual atmosphere or ocean model components could be interchanged in different combinations to generate various coupled models that could be assembled for particular applications. Current coupled model development, however, is proceeding independently at various laboratories and universities with little coordination.

Many field programs are justified in part by arguments that their efforts will lead to model improvements. It is not easy, however, to fashion new parameterizations from even the most carefully designed field programs and it is also not certain that even well-conceived new parameterizations will lead to overall model improvement. Often the difficult task of developing new parameterizations is carried out by small, academia-based research groups. The subsequent labor-intensive testing of the parameterizations in climate models requires a tailoring of code so that it complies with the unique requirements of each host model. This work could again be minimized by encouraging coding standards that facilitate sharing of common subroutines among models (e.g., subroutines for short-wave radiative transfer or for trace species transport and diffusion). While such coding standards should be encouraged when possible, it is recognized that, because some processes may be parameterized somewhat independently in one model but closely coupled in another, it may in some cases be difficult to standardize their treatment across models. Thus, it would not be appropriate to require all models to abide by a rigid set of coding standards.

Under current competition for funding, there is little incentive to coordinate development of various analysis tools among projects funded by different agencies. In particular because modeling groups engage in many common activities (e.g., model development and model evaluation), there may be opportunities to minimize duplication of effort, which might ultimately reduce the costs necessary to maintain the multiple visualization and analysis software packages that are currently supported by climate research funds. Enhanced coordination could foster the production of tools that could be used by many modeling groups, and could also be beneficial in the process of defining the types of model runs that are used in inter-model comparisons and in climate change assessments. Ultimately, enhanced coordination may yield cost savings by increasing the efficiency with which scientists can produce, visualize, and analyze model output.

Another way enhanced coordination might be manifested is in facilitating the standardization of model output. Clearly, such standardization would make it possible for common software utility routines to be developed that would aid model intercomparison and improvement efforts. Moreover, this standardization would also make it easier for scientists in other disciplines (e.g., the ecological impacts community) to access data from different models. As a relatively few widely used formats emerge, notably, netCDF and HDF, it is likely that the availability of powerful software that can only accommodate such formats will provide increasing incentives to conform to these formats, thus minimizing duplication of effort among modeling groups.

Specialists can efficiently analyze the output from several different models if standard simulations are performed and if output is archived in a standard format. Agency program managers may not need to modify their current strategies much because international projects such as AMIP and CMIP are already fostering this and attracting considerable participation and cooperation. These projects, which should be encouraged, serve to coordinate the efforts of the broader community of climate scientists evaluating climate models and make it possible for smaller groups to submit their models for closer and more comprehensive scrutiny than their own resources would permit. In principle, a single expert in a particular area can evaluate the performance of all models in the intercomparison projects with little more effort than it would take to evaluate a single model. The efficiency of this approach is becoming more evident as these projects mature. To facilitate the intercomparison of separate model analyses, the development of compatible diagnostic algorithms should be encouraged.

For intercomparison efforts to be successful, the models being analyzed must use the same initial and boundary conditions so that it is differences in the representation of model physics that are being assessed, not differences in the forcings. At present, there is no uniform set of land-surface data for use as boundary conditions in the climate models of the major U.S. modeling centers. Consistency in this regard can be maintained through enhanced coordination of U.S. high-end modeling efforts among these centers.

One way to establish the credibility of the climate models used for making climate assessments is to test their performance when run in a weather-or short-term climate-forecast mode. However, in the United States there are serious impediments to cooperation between the operational forecast facility (NCEP) and the climate modeling community. Operational forecasting facilities in the United States currently provide little support for activities other than operational ones, and therefore, inadequate human resources for collaboration with external climate modeling groups or individuals. An increase in collaborative opportunities between these entities could be beneficial to both.

Some comments were also received from members of the academic community who are eager to have early access to output from some of the computationally most demanding climate model simulations. The potential scientific benefits resulting from broad participation in the analysis of these simulations must be balanced by a recognition that the development of the models used to generate these simulations can take years, and the scientists who have developed these models deserve to reap the first rewards of their efforts in terms of publishable research.

ALLOCATING RESOURCES

Productive climate modeling efforts require an appropriate division of resources between support for personnel (including both climate and computer scientists) and computer facilities. Also essential is access to the results of process studies that lead to improved model formulations, and the collection and analysis of observational data for use in evaluating models, but these needs are outside of the scope of this report and will not be considered here.

Although the total computer resources available to the U.S. climate modeling community are substantial, inadequate access to the world's most powerful mainframes by U.S. modelers in universities and the national centers is significantly limiting progress. This view is supported by Table 1 and its accompanying text and by evidence put together by Dr. Bill Buzbee, the director of NCAR's Scientific Computing Division (see Appendix E). Buzbee has compared NCAR capabilities to those at GFDL and six research labs around the world. He has shown that “international colleagues now enjoy a substantial computational advantage over U.S. modelers.” This view is further buttressed by the USGCRP National Assessment program's current reliance on climate change scenarios developed by foreign modeling groups and by recent special arrangements to use computers at foreign institutions in order to produce complementary simulations for the National Assessment with the NCAR climate system model.

The ability of the climate community to acquire state-of-the-art mainframes is severely hampered by a Department of Commerce "antidumping order" prescribing a financial penalty in excess of 400 percent on the purchase price of the world's most powerful commercial supercomputers, which are Japanese in origin. The climate community has not been provided with the financial or computational resources to overcome this barrier and has, therefore, been unable to fully capitalize on the scientific potential within the United States. In effect, if total resource availability remains fixed, the cost of any increase in access to fast machines could require a comparable reduction in the scientific and technical personnel who develop, test, and apply models.

In allocating resources for climate modeling, agency managers should understand that there is an inherent pyramid structure in climate research. The broad base of understanding that is required in constructing climate models is obtained through a multitude of observational programs and individual process studies. The small and intermediate modeling efforts (usually involving a single component of the climate system) incorporate the relevant portions of the underlying research both during model development and in model applications. The most sophisticated high-end models are essentially built by integrating the various climate system components. U.S. agencies spend most of their resources on small and intermediate modeling. The results of this work are published in journals and are therefore freely available to the climate modeling community.

The full benefits of investing in the foundations of the pyramid can not be realized without sufficient support for the high-end modeling needed for impacts and policy purposes. A non-trivial element of a comprehensive high-end modeling system is the dissemination of the output from these models to the wider climate research and user communities — something that is largely unfunded in the United States.

In Europe a relatively high priority has been given to funding research at the top of the pyramid, which relies in part on the fundamental research carried out in the United States. There is, unfortunately, a certain nonreciprocity in this arrangement because the results of the U.S.-funded research can feed directly into the high-end modeling efforts in Europe, but, as mentioned previously, the United States does not necessarily have full, open, and timely access to output from foreign models. Solutions to this problem should not involve the imposition of access restrictions to U.S. data.

Simply acquiring hardware alone is not sufficient. We also need to invest in the development of scientific expertise and the dissemination of that knowledge. Conversely, while the United States is an intellectual leader in this field, it needs the hardware to make effective use of this intellectual capability. Thus, one of the fundamental reasons for considering additional investment in U.S. high-end modeling infrastructure is that the incremental returns on investment could be very large, as the added effort in high-end modeling could be encouraged to interact with the existing vast U.S. expertise in small/intermediate modeling. The synergism of interaction could be expected to yield substantially more than the sum of the individual modeling efforts.

RECENT DEVELOPMENTS RELEVANT TO THIS REPORT: COMPUTATIONAL CAPABILITIES AND COORDINATION

Since the climate modeling forum two years ago, there have been indications of several significant developments and changes in the U.S. climate modeling effort. Among these are the following:

- An NCAR proposal to acquire an NEC SX-4 computer was effectively denied by a Department of Commerce “antidumping order” prescribing a 400 percent financial penalty. This has precluded certain applications of the NCAR Climate System Model (CSM) and slowed its use in studies requiring multi-century simulations and may also retard the production of regionally resolved climate scenarios for the USGCRP National Assessment. This lack of routine access by climate researchers to the world's most powerful computers has become a quite serious problem that increasingly affects the international competitiveness of the U.S.

climate modeling community. This precedent-setting decision seems to have discouraged other institutions within the United States from considering the purchase of foreign computers, even though these computers might prove superior in climate model applications.

- Responding to encouragement to interface more effectively with the outside community, NCAR has made notable changes, as evidenced by their annual Climate System Model (CSM) Workshop and their CSM working group meetings, with heavy involvement of the academic community. Furthermore, the publication of a series of papers describing results from the NCAR CSM in a special journal issue (*J. Climate* **11** [6], 1998) is a good sign that U.S. coupled atmosphere-ocean modeling efforts are progressing.
- A new DOE initiative (ACPI, 1998) is under development, which, if funded, will attempt to increase by a few orders of magnitude the amount of computing power available for climate modeling applications. Under this initiative, massively parallel computing machines, currently under development for other DOE purposes, would be applied to climate modeling, including the production of multi-century, high-resolution simulation ensembles.
- At the request of USGCRP and with support from NSF, NCAR has agreed to develop some climate change scenario runs with the CSM for the USGCRP National Assessment. Some of these runs are being completed in Japan and Australia because of the current scarcity in the United States of the kind of computing resources needed for this type of model.
- A sharply upgraded version of the GFDL MOM3 ocean model has recently been released to its worldwide user community, which includes most of the major climate modeling centers.
- Two workshops were recently held at the Goddard Institute for Space Studies (GISS)—one on ocean modeling and the other on land surface modeling—to encourage involvement of the academic community in the GISS modeling effort.
- In August 1998, a workshop was held at NCEP, sponsored jointly by NCEP and NSF, to investigate the question of whether a common modeling infrastructure could enhance the degree of collaboration between NCEP and the weather and climate research

communities in the United States.

- An ad hoc working group, currently chaired by Steven Zebiak and Robert Dickinson, has been formed in response to one of the recommendations of the NCEP/NSF meeting that a group is needed to formulate coding and data standards to facilitate exchanges of data and promotion of interactions between modeling groups and the academic community. At a first meeting in Tucson in October 1998, initial steps were taken to develop standards for model parameterizations and approaches for facilitating involvement of a wider community in their development. Steps were also taken to develop agreements on standard data formats. In addition, suggestions were presented as to how standard data sets for model boundary conditions should be developed.

With respect to this report, these developments, among others, indicate that the climate modeling effort is evolving. In some cases (e.g., the denied purchase of an SX-4), a problem identified by the climate modeling community has been exacerbated, but in another, (e.g., the potential increase in computational resources through the DOE initiative), there are indications that U.S. computational capabilities could dramatically increase sometime in the future. Emerging efforts to encourage more collaboration across institutional barriers is promising. The U.S. climate modeling community will likely remain behind the rest of the world in terms of computational facilities for the next several years. Nevertheless, the United States can maintain many aspects of scientific leadership through its major satellite-based climate observing system and fostering of research and development in climate processes. Unfortunately, the U.S. community may, to some extent, have to be content to see these advances implemented in foreign models.

CONCLUSIONS.

Through our analysis of the discussions at the climate modeling forum, responses to the USGCRP questionnaire, personal contacts with the climate modeling community, and deliberations within the CRC, we have reached initial conclusions in our evaluation of the organization and infrastructure of climate modeling in the United States. These conclusions are reported in the context of the three questions referred to the CRC by the USGCRP program managers.

1. Do USGCRP agencies have a coordinated approach for prioritizing from a national perspective their climate modeling research and assessment efforts?

We find that:

- **USGCRP agencies do not have a coordinated approach.**

Climate modeling priorities within the USGCRP are primarily established by individual agencies with substantial input to each agency from climate researchers, but with little formal inter-agency coordination. There is no effective integrating national strategy and little formal consideration of the needs of the policy community.

2. Are resources allocated effectively to address such priorities?

We find that:

- **There are few monetary resources dedicated to high-end climate modeling. Further, there is insufficient access to computers powerful enough to take advantage of the U.S. intellectual capability to design and run the climate models needed to answer critical science and policy questions. In addition, there is no coordinated mechanism for establishing the priority of these questions.** The lack of resources and the inefficient assignment of those that are available are hampering progress, both in theoretical understanding of climate and in performing simulations of direct relevance to policy decisions concerning natural and anthropogenic climate variability and change.

3. How can the U.S. climate modeling community make more efficient use of its available resources?

We find that:

• **First, a national set of goals and objectives that are agreed to by the USGCRP agencies is essential.** These goals and objectives would be aimed at establishing the major themes for climate research, and would be set in the context of scientific priorities and national policy decisions. By formulating these goals and objectives, the USGCRP agencies should also agree to seek coordinated funding initiatives directed at achieving them.

• **Second, a concerted effort by the relevant agencies is needed to establish a coordinated national strategy for climate modeling.** That strategy may call for the allocation of resources to be distributed at a number of locations, and it must have the capability to deal with the complexity of high-end climate modeling. A number of formats exist for the establishment of such a resource. Appendix A identifies several possibilities, and there likely are others. What must be encouraged in such an endeavor is the increased coordination and integration of activities between national laboratories and universities. What must be avoided is a top-down prioritization of research activities driven by short-term agency agendas.

The current approach to climate modeling in the United States produces a rich diversity of research driven by individual researchers. The purpose has to be to focus that research, not subject it to the "problem of the month," which ultimately will dissipate scientific resources. While difficult to specify a priori, a carefully considered balance must be struck between policy-and science-driven research. Several examples of how the recommended coordination might be manifested are given in the body of this report.

• **Third, in order to optimally use existing scientific capabilities, adequate resources, including adequate supercomputing capabilities, need to be provided to the**

climate modeling community.

At present, the U.S. modeling community on the whole is not supported to produce climate change scenarios for the GHG-driven climate change assessments, such as IPCC and the USGCRP National Assessment. This is in part because of the limited funding for these activities and in part because of the inability of U.S. climate modeling centers to acquire state-of-the-art supercomputers. U.S. scientists do participate to the extent possible in climate change assessment activities by reprogramming resources within their limited budgets. Participation in these activities is of necessity on a volunteer, often uncoordinated and normally aperiodic basis. Unfortunately, standard tenure-track systems, which emphasize frequent, first-authored publications, do not always reward such participation. Longer-term research, which may require years of effort to achieve results, in fact, is penalized in the race to produce early papers.

The provision of financial resources should be based upon peer-reviewed proposals that advance the main themes of the agreed upon science and policy objectives. Those resources need to be committed for periods commensurate with the time required to achieve definitive results.

We agree with certain aspects of the discussions on funding in Appendix A. Merely adding funds to budgets is not effective. We agree with other statements in Appendix A that “the option of accelerating progress by simply adding funding will fail without also making major changes in the management and institutional cultures of existing centers.”

• **Fourth, the reliance of the United States upon other countries for high-end climate modeling must be redressed.** This issue is rooted in both science and policy, but can only be resolved through governmental intervention. The European modeling centers, for example, benefit from pioneering research by the United States in intermediate climate modeling; the CRC strongly supports this element of free and open exchange of climate data. Unfortunately, the United States is not guaranteed equivalent access to European model output or methodologies, although, at present, access to transient climate change simulations from foreign models is generally available to the U.S. research community. The concern over data access is due in large part to European national policies that restrict the free and open exchange of some information in favor of enhancing national commercial advantages (see Appendix D).

Until the gap in climate modeling capabilities between the United States and other countries is closed, decisions that could substantially affect the U.S. economy might be based upon interpretations of simulations (e.g., nested-grid runs) produced by countries with different priorities than those of the United States.

There is real concern that if U.S. scientists lose involvement in advanced modeling activities, they will miss opportunities to gain valuable insights into the underlying processes that are critical to subsequent modeling investigations Further, the state of climate modeling throughout the world is such that the addition or removal of even a single model would affect the confidence levels assigned to certain scenarios of future climate change. In other words, not only would the United States benefit from enhancements in its modeling capabilities, the international community would benefit from these efforts as well.

In essence, the CRC finds that the United States lags behind other countries in its ability to model long-term climate change. What computational and intellectual capability it does possess is neither well focused nor well financed. Those deficiencies have a significant and negative impact on the United States:

1. to predict future climate states and thus:

a) assess the national and international value and impact of climate change;

b) formulate policies that will be consistent with national objectives and be compatible with global commitments;

2. to most effectively advance understanding of the underlying scientific issues pertaining to climate variability and change.

Thus, to facilitate future climate assessments, climate treaty negotiations, and our understanding and predictions of climate, it is appropriate to develop **now** a national climate modeling strategy that includes the provision of adequate computational and human resources and that is integrated across agencies.

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Appendix A

To: Bob Corell, Mike Hall, Charles Kennel and Ari Patrinos

From: Tim Barnett, David Randall, Bert Semtner and Richard Somerville

Subject: Strengthening the United States National Climate Modeling Effort

Date: October 21, 1995

1. THE CRISIS IN U.S. CLIMATE MODELING

Many climate researchers in the United States and abroad realize that the U.S. is no longer the world leader in climate modeling. Today, Germany appears to be in first place, with the United Kingdom in second. The U.S. is at best third and may well be lower. By any measure, the American effort is falling seriously behind that of Europe and, perhaps, Japan. The current crop of U.S. models is technically less sophisticated, observationally less well verified, and physically less complete than the best foreign models.

This need not be so. American scientists are as talented and as well educated as those abroad. We enjoy generally adequate funding in the modeling area, and except for a few years in the 1990s we have had the world's most powerful computers at our disposal. General circulation models of both the atmosphere and the ocean were first developed in the United States. Today, however, as the generation of American scientists who pioneered climate modeling approaches retirement age, there is a crisis in the field. Unless the U.S. moves quickly and decisively to reinvigorate its effort, it may be relegated to permanent second-class status in this critical area of Earth science research.

Our purpose in this memo is first to briefly outline three strategic options for regaining the lead in global climate modeling that the U.S. enjoyed as recently as the early 1980s. Then, we argue for adopting one of these three options.

2. THREE OPTIONS FOR PROGRESS

Option 1: Further increase funding at existing modeling centers

The government might simply increase the funding and thus the level of effort at one or more of the existing climate modeling centers. Indeed, much excellent research has already come from these centers, which developed some of the first modern climate models. Additional funding would surely have some positive effect.

In our view, however, it is not money which has been the primary rate-limiting factor in the progress made recently at these centers. Instead, we think that organizational and managerial factors, together with personnel issues, have kept these centers from maintaining the lead they once held. Too often, relevant research by outstanding scientists, at a variety of U.S. institutions, has not been well-integrated into the modeling efforts. In particular, the centers have not benefited optimally from scientific advances made elsewhere, especially in academia, despite the fact that the U.S. has a proud history of climate model development in academia, dating back to the 1960s, and including some very important work.

In sum, we think that the option of accelerating progress by simply adding funding will fail without also making major changes in the management and institutional cultures of the existing centers.

Option II: A new center for climate modeling

A new modeling center could be created. This would be a hard sell politically in these austere times, given that several modeling centers already exist. In addition, it is unlikely that many of the best scientists would willingly leave their present positions to staff the new center.

Option III: A distributed national climate modeling program

We believe that creating a Distributed National Climate Modeling Program is the most promising strategy for the U.S. to regain international preeminence in global climate modeling. A prototype distributed program already exists in the form of DOE's CHAMMP program. CHAMMP, which is distributed over multiple laboratories and universities, has successfully brought together specialists in ocean/atmosphere processes, numerical methods, and computer applications. Under the auspices of CHAMMP, we have seen the development of a close collaboration involving NCAR, GFDL and several university groups with the Los Alamos National Laboratory to implement two different oceanic general circulation models and an atmospheric general circulation model on massively parallel computers. A Distributed National Climate Modeling Program could be built on the CHAMMP framework. Such an effort would require multi-agency funding and management. It would also require a focusing of effort and a directed management approach to the science and engineering aspects of the program. One key is good management of people and existing resources. Good management will not suffice, however, without good scientific ideas.

3. A THREE-TIER STRUCTURE FOR THE DISTRIBUTED PROGRAM.

We envision a Distributed National Climate Modeling Program with three elements, or tiers.

Tier 1: The U.S. National Climate Model

Tier 1 would maintain and make available to a community of users a single U.S. National Climate Model, initially encompassing the atmosphere, oceans, sea ice, and land surface, and eventually extending to the full climate system, including biogeochemical aspects. The National Climate Model need not be centralized at a single institution, however, particularly now that we have entered the era of the network. Computing, model development, and even consultation can be spatially distributed.

We emphatically do not advocate that the U.S. have only one climate model, both because model development can benefit from competition, and also because groups dedicated to model development need to maintain control of their own research strategies. We do believe, however, that it is important that the U.S. have a single formally designated National Climate Model, and that the climate modeling expertise that is distributed throughout the U.S. flow effectively and continuously into this model, in order to keep it at the very forefront of the state of the art.

We also consider it essential that the national Climate Model support a large community of users, in order to ensure thorough testing and evaluation. A significant level of infrastructure would be needed to support this user community. A history of strong feedback from a large and active user community is one reason that the Europeans dominate today. We advocate, therefore, that groups in U.S. universities and national laboratories which are performing climate simulations but are not focused on model development should be strongly encouraged to use the U.S. National Climate Model.

Tier 2: Model development research

Tier 2 would provide a solid foundation of climate model development research to feed into the National Climate Model. This model development research should not be centralized or regimented and need not be based directly on use of the National Climate Model itself, because the best new ideas can come from anyone, anywhere. In particular, model development research should continue to occur both in national laboratories and in universities.

The academic community is especially well positioned to produce new discoveries and innovation. As already mentioned, the U.S. has a proud tradition of such work. University-based model development groups are needed to train the next generation of modelers. Students do not learn the art of climate modeling simply by running a community model developed in a distant laboratory by people with whom they have little interaction. Aspiring young modelers can learn best through close, student-advisor interactions with those who are actually developing the next generation of models.

We advocate that model-development research in academia consist of two categories of efforts. The first would consist of a few Academic Model Development Centers set up at sites chosen via proposal, and funded for perhaps five years at a time, each at levels of up to several million dollars per year. The Academic Model Development Centers would operate in a manner similar to the NSF Science and Technology Centers. Much of the funding needed to support the Academic Model Development Centers could come from judiciously identifying and eliminating existing sub-critical modeling efforts.

The Academic Model Development Centers would not be responsible for providing community modeling services. The responsibilities of the Academic Model Development Centers would be to create new ideas that would be funneled into the National Climate Model and to train students. It is essential to set up and maintain a well-defined mechanism to ensure that ideas are in fact effectively transferred from the Academic Model Development Centers to the U.S. National Climate Model. The lack of such a mechanism today is a major reason for the weakness of the U.S. modeling effort.

There should also be a larger number of smaller university-based climate modeling projects, each of which might focus on one particular aspect of model development. These smaller efforts would be arranged more informally, essentially through the standard proposal and peer review procedure, but we think that it is important to acknowledge explicitly that such small projects can and should make important contributions to the overall national effort.

Tier 3: Research on climate variability

Tier 3 would consist of a strong program to explore climate variability systematically, based on a hierarchy of models and statistical methods, and centered around model applications and understanding of the basic physics of climate processes as represented through the development of simplified models, rather than numerical model development. Tier 3 activities should occur in both universities and laboratories. It is important that the Tier 3 research involving climate model applications be based on use of the National Climate Model, rather than on a hodgepodge of models from a variety of sources, so as to maximize feedback on the performance of the National Climate Model.

4. IMPLEMENTATION

It is our view that through the three-tier, Distributed National

Climate Modeling Program described above, the United States can regain world leadership in climate modeling. We suggest that these concepts be set down and developed further in a concise National Climate Modeling Plan, which should be focused on the production of practical results. The National Climate Modeling Plan would be revisited once per year.

Implementation of our suggestion would bring about several key changes from the current situation. First, the U.S. would soon have an officially sanctioned, world-class National Climate Model, supporting a large user community and producing results needed by policy makers and others. Second, a system of designated Academic Model Development Centers would be put into place, and a formal mechanism would be set up to ensure that high-quality new ideas are promptly implemented in the National Climate Model. Third, the U.S. would have a clearly defined, interagency National Climate Modeling Plan that would spell out how the contributions of the various participants in the U.S. climate modeling effort fit together to make a coherent but decentralized national climate modeling research enterprise.

We think that the participation of the scientific community is essential for putting such a program in place. We advocate a high-level review of the current status of the U.S. climate modeling effort.

We would welcome the opportunity to discuss this proposal with you and to help in implementing the program.

Appendix B

Statement of Task

The CRC will prepare a brief report that assesses the capacity of the U.S. climate modeling community to support national and international climate assessments, including an evaluation of the allocation and availability of computational resources for this purpose. The report should address three issues relevant to the climate modeling effort within the purview of the USGCRP:

1. Do USGCRP agencies have a coordinated approach for prioritizing from a national perspective their climate modeling research and assessment efforts?
2. Are resources allocated effectively to address such priorities?
3. How can the U.S. climate modeling community make more efficient use of its available resources?

These issues should be addressed in the context of other international climate modeling activities. The report should not contain recommendations, but should include findings and conclusions with supporting analysis and discussion.

Appendix C

CRC Climate Modeling Workshop Invitation and Agenda

Dear Friends of the Climate Research Committee:

The Climate Research Committee (CRC) of the National Research Council (NRC) and the Office of the U.S. Global Change Research Program invite you to participate on 11 and 12 June 1996 in a discussion of the Quality and Infrastructure of Climate Modeling in the United States. This discussion is being held in Washington, D.C. as part of a meeting of the CRC. Representatives of the federal agencies that support climate modeling are expected to attend this meeting. Those federal representatives, as they allocate resources and organize the government's support of climate modeling, are greatly interested in the thoughts of the scientific community involved in climate modeling. The CRC will also use this discussion as it prepares recommendations to the federal agencies and to the research community of the future of climate modeling. The agenda of the complete meeting follows this message.

We are working hard to ensure a broad spectrum of scientists involved in all aspects of climate modeling at this meeting and believe that your perspective can provide a valuable contribution to the discussions. We look forward to seeing you.

Sincerely,
William Sprigg
Director
Board on Atmospheric Sciences and Climate

AGENDA OF CLIMATE MODELING WORKSHOP

TUESDAY, 11 JUNE

Executive Session

7:30 a.m.	Breakfast available in room and refectory
8:00 a.m.	Executive session Eric Barron, chair
11:30 a.m.	Lunch in refectory

Public Session

The Quality and Infrastructure of Climate Modeling in the United States

Climate modeling is a large complex enterprise. It requires modeling not only the atmosphere, but also modeling of conditions at the lower boundary involving the oceans, land surface (especially vegetation), surface hydrology, cryosphere, and sources of atmospheric constituents (such as carbon dioxide, methane, aerosols, and CFCs). Observational data must be obtained, assimilated, and archived. Model development and access must be managed. Model output must be archived, made available, and analyzed. This study session, sponsored by the NRC and the USGCRP, will examine ways to improve the quality and infrastructure of climate modeling in the United States.

12:30 p.m.	Introduction to session and review of the agenda Tom Karl, chair
12:40 p.m.	The impetus for this discussion of climate modeling Mike MacCracken
12:50 p.m.	What issues related to the quality and infrastructure of climate modeling face the federal agencies (especially those participating in the Interagency Modeling and Prediction Working Group)

	IMAP WG representative
1:10 p.m.	What issues face the scientific community related to the quality and structure of climate modeling? How should the CRC address the issues facing both the federal agencies and the scientific community?
	Tom Karl
1:40 p.m.	Self introductions around the room. Participants will be asked for a few words on what they would like to see as the results of this meeting.
2:00 p.m.	Summary of the major areas of agreement and disagreement in responses to the questionnaire on modeling from the USGCRP V. Krishnamurthy
2:20 p.m.	The key conclusions and response to the General Accounting Office report on "Global Warming: Limitations of General Circulation Models and the Costs of Modeling Efforts" GAO representative
2:30 p.m.	Break
2:50 p.m.	What are the strengths and weaknesses of climate modeling in the United States? What impediments are there to improving the U.S. modeling effort?
3:20 p.m.	How does the U.S. climate modeling effort compare to modeling efforts in other countries?
3:50 p.m.	What steps should federal agencies take to improve the quality and usefulness of climate models?
4:20 p.m.	What steps should the scientific community take to improve the quality and usefulness of climate models?
4:50 p.m.	Review of plans for Wednesday
	Tom Karl
5:00 p.m.	Adjourn for day

7:30 p.m.	Working dinner for session chair, discussion leaders, and invited guests
WEDNESDAY, 12 JUNE	
8:00 a.m.	Breakfast available in room or refectory
	Continuation of discussion on the "Quality and Infrastructure of Climate Modeling in the United States"
8:30 a.m.	Developing consensus recommendations for improving the climate modeling effort in the United States Tom Karl, chair
8:40 a.m. agencies?	What should the CRC recommend to the federal
10:20 a.m.	Break
10:40 a.m.	What should the CRC recommend to the scientific community?
12:20 p.m.	Summary
	Tom Karl
12:40 p.m.	Lunch in refectory
1:40 p.m.	Depending on the level of agreement reached in the morning session, the discussion will continue or the CRC will meet in executive session to begin preparation of a report on the results of the session on the quality and infrastructure of climate modeling in the United States.
2:30 p.m.	Break
2:50 p.m.	Executive Session
4:00 p.m.	Adjourn meeting

Appendix D

Examples of Access Restrictions on Foreign Atmospheric Data.

1. Real-time access to weather and seasonal-to-interannual climate forecasts from the European Center for Medium-Range Weather Forecasting is restricted. The U.S. National Weather Service and certain climate research centers (e.g., IRI) can obtain access to these data through institutional agreements, however real-time access by individual U.S. researchers is generally denied. U.S. commercial interests are also denied real-time access to these data.
2. The U.K. Meteorological Office (UKMO) maintains a data base of climate data at: *http://www.meto.gov.uk/sec5/CR_div/index_climate.html*. Access to these data is only possible through individual agreements with the UKMO and access is not guaranteed if the data are to be used for commercial or business purposes.
3. The Canadian Centre for Climate Modeling and Analysis makes its model output available to the research community. However, access to these data is not readily available if the data are to be used "as a part of, or as the basis of a data base, product, or service

for access or distribution outside of [an] organization, or for commercial sale."

4. The IPCC Data Distribution Centre does not allow commercial use of its data. (see, e.g., *http://ipcc-ddc.cru.uea.ac.uk/*)
5.

Memorandum

FROM: Elbert W. Friday, Jr., Permanent Representative of the United States to the WMO (1988 – 1998)

TO: Tom Karl

DATE: July 2, 1998

RE: Limitations on International Exchange of Climate Model Output

Over the past ten years, most of the governments of Western Europe have moved from taxpayer-funded meteorological services to ones that are increasingly being asked to recover a substantial portion of their costs of operation. This has given rise to some degree of conflict in the field of international meteorology where data and products, once eagerly exchanged without restrictions, now have intrinsic economic value. We are seeing increasing reluctance on the part of several meteorological services to provide data and products without restrictions being placed on their use or redistribution.

In 1995, the World Meteorological Organization (WMO) passed a resolution (Res 40, Congress XII) that tried to continue the free and unrestricted exchange of environmental data and products. This resolution recognized that some services may be required to place certain restrictions on their products and established the conditions for data distribution among countries.

During the discussions leading up to the resolution, the Director of the British Met Office, Prof. Julian Hunt, stated that he did not intend to make any of his climate projections publicly available as they were too valuable commercially to give away. This practice could have the impact of denying US economic interests the latest in climate forecasting capabilities if the US capability falls behind that of other countries.

Appendix E

November 25, 1997

Dr. Tom Karl
Chairman, Climate Research Committee of the National Research Council
Harris Building, Room 466 2001 Wisconsin Avenue, NW Washington, DC 20007

RE: Climate Research Committee of the National Research Council Review and Assessment of Climate Modeling Activities in the U.S.

Dear Dr. Karl:

Per your request of November 3, 1997, we are pleased to provide the enclosed attachments:

1. **NCAR measurements of single processor performance.** The enclosed table summarizes a small set of measurements that we find useful for preliminary evaluation of computers. For example, many atmospheric With respect to computational kernels, "radabs" is a physics module models make heavy use of elementary functions so we measure them. from the NCAR Community Climate Model (CCM). The "shalxx" entries are for a 2D shallow water model at two grid sizes -64 × 64 and 256 × 256. Our experience is that results from these kernels typically provide an upper bound on the performance of a specific computer relative to a broad set of atmospheric models. Because overall performance is often paced by memory performance, "copy" measures memory to memory transfer, "ia" measures indirect addressing, and "xpose" measures

transposition of arrays, which is fundamental to the implementation to the FFT. Probably the most important metric in this table is the performance of CCM2.

As you will note, the first five columns of the enclosed table give performance on leading edge microprocessor systems. The last two columns give performance for two parallel vector processing systems-the Cray C90, a second-generation vector computer, and the NEC SX-4, a state-of-the-art vector computer. Relative to the SX-4, microprocessors deliver from 7–17%, i.e., approximately $1/10^{th}$, of the performance of state-of-the-art vector processors. While the cycle time (MHz) of microprocessors now surpasses that of vector processors, our measurements show that for the past decade, the ratio of sustained performance between the two is approximately 10, in favor of vector processors. Thus, if one can achieve a certain level of performance, say 20 Gflops, using *n* vector processors, typically at least 10 *n* microprocessors are required to achieve the same level of performance.

2. A Sampling of Computing Systems in Major Atmospheric Modeling Centers Around the World. Simply put, our international colleagues now enjoy a substantial computational advantage over U.S. Modelers.

3. Comments from NCAR to the International Trade Commission. This document includes information as to our objectives in the procurement, details of the competing offers, and our rationale for selecting the SX-4.

Thank you for the opportunity to supply this information. If I can be of further assistance, please let me know.

Sincerely,
Bill Buzbee,
Director
Scientific Computing Division
National Center for Atmospheric Research

cc: R. Serafin, R. Anthes, C. Jacobs, J. Fein

NCAR MEASUREMENTS OF SINGLE PROCESSOR PERFORMANCE

High-end Processors

(64-bit Results)

	DEC 8400/ EV5	**HP** PA-8000	**IBM** R6K/590	**SGI** R10K	**SUN** Ultra2	**CRAY** C90/1	**NEC*** SX-4/1
Date Measured	*11/96*	*8/97*	*1/97*	*9/97*	*7/97*	*2/97*	*2/96*
Clock (MHz)	440	180	77	196	250	240	109
Peak (mflops)	880	720	154	392	500	960	1744
Elementary Function (millions results per second)							
alog	4.5	4.9	1.2	4.4	2.6	12.7	34.6
exp	4.4	5.5	1.4	4.0	1.7	14.2	40.7
pwr	2.6	1.4	.41	2.7	.74	3.5	10.4
sin	3.7	2.6	1.5	4.0	1.2	8.1	39.5
sqrt	7.6	11.6	1.9	5.4	9.1	34.2	46.7
Computational Kernels (mflops)							
radabs	90.8	112.5	20.4	115.1	64.6	447.0	865.9
shal64	123.2	208.3	80.3	160.7	100.7	510.0	
shal256	54.5	87.6	73.6	46.1	51.3	633.2	
Memory Performance—Max measured over all vector lengths tested (mb/s)							
copy	99.6	180.5	419.4	66.5	151.0	3508.6	6809.0
ia	76.5	78.2	167.8	78.9	139.6	2516.8	1905.3
xpose	81.8	166.0	139.8	67.4	137.4	2140.0	3348.0
CCM2 Performance							
(seconds/ day)	471.9	537.5	1131.9	636.8	680.4	124.2	81.3
(mflops)	96.5	84.8	40.2	71.5	66.9	366.6	560.0

* Production models of the SX-4 are 15% faster than the prototype used in this measurement.

A SAMPLING OF COMPUTING SYSTEMS IN MAJOR ATMOSPHERIC MODELING CENTERS AROUND THE WORLD

by
Bill Buzbee, Ph.D.
Director, NCAR Scientific Computing Division
November 25, 1997 (revised February 6, 1998)

I. Introduction

The National Center for Atmospheric Research (NCAR) and the community it serves, currently enjoy world leadership in several areas of atmospheric sciences research that depend on high performance computing. In order to maintain this leadership, NCAR must have computing capabilities that are comparable to peer organizations throughout the world. The most powerful computer that NCAR has today is the Cray C90/16 and NCAR will soon install a 128 processor Distributed Shared Memory (DSM) microprocessor system. Neither of these systems will sustain more than 5 Gflops on a single application. However, NCAR's peer centers in Australia, Canada, England, and elsewhere, are installing systems that by January '98 will sustain from 20–100 Gflops on a single application. With these systems, they can, and they are, conducting research that is far beyond the ability of their U.S. counterparts.

Section one of this paper summarizes the computing capabilities of a small number of forecast and climate modeling centers around the world. Sections two and three discuss future plans at some of these centers. Section four summarizes computing capability at a small number of universities in Japan and Europe. Section five discusses the impact on U.S. atmospheric science. Overall, this paper shows that modelers outside of the U.S. have a substantial computational advantage over their U.S. colleagues and are likely to enjoy such for several years.

II. Systems Currently Installed

Table 1 lists some of NCAR's peer organizations and their associated computing systems that are capable of sustaining 20–100 Gigaflops on a single application.

Table 1: What's Happening Abroad?

Center	System	# of Processors	Capability Gflops
ECMWF	Fujitsu/VPP	116	80 – 100
Canada	NEC/SX-4	64	40 – 50
UK Met	Cray T3E	700	~ 35
France	Fujitsu/VPP	26	20
Denmark	NEC/SX-4	16	12
US GFDL	Cray T90	26	15
Australia	NEC/SX-4	32	20 – 25

In 1995, the **European Center for Medium Range Weather Forecasting** (ECMWF) selected the Fujitsu Vector Parallel Processor (VPP) system via competitive procurement. As of August 1997, the system has 116 processors, each of which sustains about 0.75 Gflops, giving the possibility of sustaining 80–100 Gflops on a single application. ECMWF is using the VPP to run the climate version of their forecast model (used in seasonal forecasts) at T63L50 resolution [1]. In contrast, the NCAR Community Climate Model, Version 3 (CCM3), is typically run at T42L18. To move the UCAR CCM3 to a configuration similar to that being used at ECMWF would require a machine that can sustain at least 20 Gflops.

The **Canadian Meteorological Center** (CMC) has a 32 processor NEC SX-4. The CMC set a milestone recently by completing a 24-hour forecast over North America at 10-km resolution in about forty minutes of wallclock time [2]. CMC was able to do this because the SX-4 sustains about 24 Gflops when executing the MC2 forecast model, thus CMC plans to reduce its operational forecast grid size to 10–15 km [3]. By January of 1998, CMC will have two SX-4/32s and by January of 2000 they will have four SX-4/32s that can be clustered into a single 128 processor system via NEC's fiber optic Internode Crossbar

Switch [4] giving them an 80–100 Gflop capability. These machines will also be used for climate modeling [3].

In the spring of 1996, the **UK Meteorological Office** (UK Met) selected the Cray T3E with 696 processors but has not yet put it into operational use. They plan to dedicate 144 processors to the global operational forecast and 144 to the regional forecast. The remaining 408 processors are to be used for research, including climate modeling [5]. This equipment is also used by the Hadley Centre.

Meteo-France has selected the Fujitsu VPP and currently has a system with 26 processors capable of sustaining 20 Gflops on a single model.

The **Danish Meteorological Institute** has two NEC SX-4s, one with sixteen processors and one with four. The sixteen processor system sustains approximately 12 Gflops. Twenty percent of the wallclock time on this machine is used for forecasting, the remaining eighty-percent and the four processor system are used for research including climate modeling [6].

The most powerful system in the U.S. that is used for climate modeling is a Cray T90 with twenty-six processors at the **Geophysical Fluid Dynamics Laboratory** (GFDL) in Princeton, New Jersey. A single processor of the T90 sustains about 0.6 Gflops when executing the NCAR CCM; thus the GFDL machine is capable of approximately 15 Gflops.

The **Australian Bureau of Meteorology** has selected the NEC SX-4 [7]. The current system has sixteen processors, but will be upgraded to thirty-two processors in February 1998. A second SX-4 with twenty processors will be acquired in the third quarter of 1999. The two systems will be clustered via NEC's Internode Crossbar Switch, thus giving a 30–40 Gflop capability.

III. Future Developments Abroad

By 1999, the next generation of Japanese vector systems will probably be available with processors that may be more than twice as fast as the current generation. If so, it will be possible to sustain 80–100 Gflops with fewer than 50 processors and, obviously, implementing and managing models over 30–50 processors is much easier than over hundreds of processors.

The Japanese Science and Technology Agency has established an "Earth Simulator" project [8]. The project was launched in April 1997 with funding of approximately $400 million over five years. The project includes development of a high performance parallel computer with a sustained performance of one or more Teraflops by 2001. This system will be provided by either NEC or Fujitsu. For example, if the next generation Fujitsu VPP has a sustained performance of 2–3 Gflops per processor, then a few hundred of these processors could sustain one or more Teraflops.

IV. A Sample of Computing Systems in Universities Abroad.

The National Science Foundation provides university scientists, including atmospheric scientists, with access to high performance computers. The most powerful computer supported by NSF is a 7.5 Gflop (twelve processor) Cray T90 located at San Diego. In contrast, the University of Stuttgart, the Swiss Center for Scientific Computing, and Osaka University have large SX-4s. The University of Tokyo, Nagoya University, and Kyushu University all have Fujitsu VPPs with at least forty processors. Thus, all of these universities have systems that are capable of 20 Gflops or more.

V. Impact on U.S. Atmospheric Science

U.S. atmospheric science modelers currently enjoy global leadership in several areas of research that depend on high performance computers. To maintain that leadership, they need computing capabilities that are comparable to their international peers. For example, a 1-km regional forecast using 4DVAR with full physics adjoint is feasible, but to use such in time critical (less than one hour) forecasting will probably require a machine that can sustain at least 50 Gflops [9]. Another example is a recently developed NCAR global chemistry model (MOZART)-in order to complete 100-year simulations of the climate within a reasonable timeframe, this model needs a computer that can sustain 20 to 40 Gigaflops [10].

The situation is particularly acute in climate modeling and is exemplified by the computational requirements of the NCAR Coupled System Model (CSM). Now that the CSM project has successfully completed a 350-year control run, there are two major studies that it would like to undertake:

1. simulate the past 120 years of climate under at least six scenarios and four sensitivity studies per scenario and
2. simulate the next 200 years of climate under at least three scenarios and four sensitivity studies per scenario.

The total years to be simulated in 1) and 2) is 5280. At present, the flagship computer of the NCAR Climate Simulation Laboratory (CSL) is a Cray C90 that sustains 5 Gflops and that serves nine USGCRP projects including the CSM. On average, the CSM project can complete 100 years/month using the CSL C90. Thus, to complete 1) and 2) would require more than four calendar years, which is unacceptable relative to progress being made by our international peers.

The CSM project also plans future improvements to the model such as semi-Lagrangian dynamics, prediction of cloud water, and a sulfate aerosol model. These improvements are expected to quadruple the amount of computation required per simulated year. Thus, a 20 Gflop machine will be required to maintain the current average of 100 years/month.

For ease of reference, we denote 1) and 2) as Part A of the CSM science plan. Similarly, we denote development and execution of the next generation of CSM as Part B of the CSM science plan.

Now that the U.S. Department of Commerce has issued an antidumping order against Japanese high performance computers, NCAR plans to continue operating the CSL C90 in FY98-99 and to install a 128 microprocessor, Distributed Shared Memory (DSM) system in the CSL in mid-FY98. Based on measured performance of two leading-edge 128 processor DSM systems executing the NCAR CCM (Community Climate Model) and POM (Parallel Ocean Model), we estimate that 128 processor DSMs will sustain about 5.0 Gflops on the CSM by mid-FY98. If so, then Part A of the CSM science plan can probably be completed by end of FY99.

However, we believe that it will be FY99-00 before 256 processor DSMs can approach 20 Gflops. Thus, the following **are not possible** in the near term:

- Part B of the CSM science plan,
- a 1-km regional forecast with 4DVAR in less than one wallclock hour, and
- routine use of MOZART in climate studies.

VI. Summary

Meteorological organizations outside the U.S. either have or soon will have computing systems that can sustain 20–100 Gflops on climate simulations, high resolution forecasts, etc. With these systems, they can and they are conducting research that is far beyond the ability of their U.S. counterparts.

The bottom line-earth systems modelers outside the U.S. have a substantial computational advantage over their U.S. colleagues and are likely to enjoy such for several years.

1. James Hack, NCAR CGD Division, personal communication, November 1997.
2. *NEC SX-4'S REAL-TIME 24HR 10 KM RES FORECAST DETAILED,* HPCwire, August 1, 1997.
3. *CMC PLANS TO REDUCE FORECASTING GRID SIZE WITH NEC SX-4,* HPCWIRE, November 20, 1997.
4. *CMC UPGRADES NEC SX-4 TO IMPROVE FORECASTING,* HPCWIRE, November 21, 1997.
5. Dr. Paul Cluey, UK Met, personal communication, November 1997.
6. Dr. Leif Laursen, Danish Meteorological Institute, “Technical Advances in Short Range Weather Forecasting”, RCI European Member Management Symposium X, Rome, Italy, October 1997.
7. AUSTRALIAN *METEOROLOGISTS, RESEARCHERS TO RECEIVE NEC SX-4,* HPCwire, July 25, 1997.
8. Hisashi Nakamura, Director of Research for Computational Earth

Science, Research Organization for Information Science and Technology, Tokyo, personal communication, November 1997.

9. Bill Kuo, NCAR MMM Division, personal communication, November 1997.
10. Stacy Walters, NCAR ACD Division, personal communication, November 1997.

COMMENTS FROM UCAR TO THE INTERNATIONAL TRADE COMMISSION HEARING

August 27, 1997
By
Dr. Bill Buzbee
Director, NCAR Scientific Computing Division

Members of the Commission:

On behalf of the University Corporation for Atmospheric Research (UCAR), thank you for this opportunity to present information on the issue before you.

UCAR RFP B10-95P requested computers that could demonstrate robust operation and high performance when executing UCAR applications. Specifically, the RFP stated (pg. 2):

> "1. The requested system will be a production-level, high-performance computing system. Production implies a high level of system availability and reliability, and both a robust batch capability and robust software development environment.
> 2. The primary objective … is high performance in executing existing parallel multi-tasked and/or message passing atmospheric models, ocean models, and/or full Climate System models…"

Hereafter, we will refer to 1. as "UCAR's robust operational requirement."

The final Best and Final Offer (BAFO) from Cray Research was received February 28, 1996. It detailed an ensemble of eight computers spanning five different system models and both vector and nonvector architectures. Only one of the eight systems could be tested with respect to UCAR's robust operational requirement and the performance measured on it was 5.4 billion arithmetic operations per second (Gigaflops). The final array of equipment, to be delivered in August '98, was estimated by Cray Research to sustain 50.3 Gigaflops. The one system that was tested would have been removed in August '98 and none of the August '98 systems could be tested. The inability to test any of the August '98 systems presented unacceptable risk to UCAR.

In contrast, all of the equipment offered by the Federal Computer Corporation (FCC) could be tested and it demonstrated both robust operation and high performance. Simply put, Cray Research lost this procurement because their BAFO had unacceptable technical risk.

Background

UCAR is a nonprofit Colorado membership corporation engaged in scientific and educational activities in the atmospheric and related sciences. With a membership of 62 universities, UCAR manages the National Center for Atmospheric Research (NCAR), under contract for the National Science Foundation. A major component of NCAR's mission is to provide state-of-the-art research tools and facilities to the U.S. atmospheric sciences community. These facilities include high performance computers.

NCAR has a long history of leadership in advancing technology for understanding and predicting the Earth's system. This research includes long-term development, documentation, and support of numerical models that require high performance computers. Thus, plans for acquiring and providing high performance computers are coordinated with plans for research projects that need these computers.

A New NCAR Climate Model

In 1995, NCAR scientists began development of a new climate model that substantially advances the state-of-the-art in climate modeling[1] and this model requires a very high performance computer.

[1] “Model Gets It Right-Without Fudge Factors,” AAAS Science, Vol. 276, 16 May 1997, pa. 1941.

For example, if this model is run 24 hours per day on a computer that can sustain 5 Gigaflops, approximately 16 calendar days are required to simulate 100 years of climate. In the course of a single scientific study, scientists routinely need to simulate several climate scenarios and perform several sensitivity studies for each scenario. Thus, a single scientific study may involve 20 or more 100-year simulations. By October '98, the successor to this model will require a computer that can sustain approximately 25 Gigaflops in order to complete a single 100-year simulation within approximately two weeks of calendar time. The computational requirements for this and similar models were considered when the RFP was developed.

The RFP

The RFP was open to computers of any architecture, e.g. vector, nonvector, massively parallel, etc. The RFP included a benchmark suite of computer programs that were designed to verify robust operation and to measure performance. The benchmark suite was provided to 14 supercomputer vendors for their critique prior to the release of the RFP. This was done to assure UCAR that the benchmark suite was objective and could be readily executed on a variety of computer architectures.

In March '95, the RFP was formally released to the 14 vendors: 12 U.S. manufacturers and two foreign manufacturers. The RFP included the option for vendors to bid on one or both of two scenarios:

A three-year scenario	
(a) funding commitment	-$13.25M
(b) performance expected	-5 Gigaflops by mid '96
A five-year scenario	
(a) funding commitment	-$35.25M
(b) performance expected	-5 Gigaflops by mid '96
	25 Gigaflops by Oct '97
	50 Gigaflops by Oct '99

All vendors were given two opportunities to ask questions and request clarifications to the RFP.

Four of the 14 vendors responded and three of those were within the competitive range. UCAR required each vendor to perform a

Live Test Demonstration (LTD) using the benchmark suite and the first LTDs were performed in August and September '95.

In October '95, UCAR issued guidelines for preparing a BAFO. The guidelines stated "…UCAR is prepared to accept a major change in system architecture and programming environment …" Also, UCAR required that each vendor perform a second LTD and these LTDs were undertaken in February '96.

Performance Expectations in the BAFO Guidelines.

In its guidelines for preparing the BAFO, UCAR suggested that the vendors focus on the five-year scenario and UCAR refined its expectations of performance for this scenario:

By October '96

(1) at least one system that could sustain 5 Gigaflops when executing the NCAR community climate model from the benchmark suite, and
(2) an aggregate capacity of at least 20 Gigaflops. By October '98
(3) at least one system that could sustain approximately 25 Gigaflops when executing the NCAR community climate model as specified in the BAFO guidelines, and
(4) an aggregate capacity of at least 45 Gigaflops.

Items 1) and 3) reflect the needs of the new NCAR Climate Model discussed previously. Items 2) and 4) could be met by offering an ensemble of systems. Item 1) was mandatory.

The BAFO from the Federal Computer Corporation (FCC)

The FCC BAFO provided:

one SX-4/32 to be delivered shortly after signing of the contract; a second SX-4/32 to be delivered October 1, 1997; two additional SX-4/32s to be delivered October 1, 1998.

The February '96 LTD verified that the FCC BAFO met UCAR's robust operational requirement. The LTD also demonstrated that FCC met items 1), 2) and 4) of UCAR's performance expectations; specifically,

- A single SX-4 executed the benchmark for item 1) with a sustained performance of approximately 13 Gigaflops.
- With regard to item 2), the UCAR LTD for the SX-4 was conducted on a prototype machine with a 9.2 nanosecond cycle time. The prototype SX-4 executed the benchmark for item 2) with a sustained performance of 18 Gigaflops. Production versions of the SX-4 operate with an 8.0 nanosecond cycle time, so a production SX-4 will deliver 20.7 Gigaflops for item 2).
- The prototype SX-4 sustained 17 Gigaflops when executing the benchmark for item 3). Production versions of the SX-4 will deliver 19.5 Gigaflops. Further, the prototype SX-4 sustained 24 Gigaflops when executing a benchmark that is closely related to the benchmark for item 3).
- Since a production version of the SX-4 is projected to sustain 20.7 Gigaflops for item 2), it follows that the FCC BAFO meets item 4). Overall, the NEC SX-4/32 is by far the fastest computer that UCAR has ever evaluated.

The BAFO from Cray Research

After an amendment to its BAFO (see Ref. [1]), Cray Research offered an ensemble of vector and non-vector equipment that involved one system in May '96, two systems in September '96, and five systems in August '98.[2]

Cray Research could only perform the LTD on the May '96 system and this system demonstrated the ability to meet UCAR's robust operational requirement. However, this system only met item 1) of UCAR's performance expectations and the BAFO required removal of this system in August '98.

Basis for Selection

Three factors weighed heavily in evaluating the FCC BAFO and the Cray Research BAFO:

a) FCC demonstrated that all of its equipment for the five-year scenario met UCAR's robust operational requirement, and met items 1),2), and 4) of UCAR's performance expectations.

b) Cray Research could demonstrate only one machine-the May '96 system-that met UCAR's robust operational requirement and its performance only met 1); this system would have been removed in August '98 and none of the systems to be installed in August '98 could be tested.[3]

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[2] For details, see amended Attachment II to UCAR's response to the Purchaser's Questionnaire, July 31, 1997.

[3] Counsel for Cray Research has noted that at the conclusion of the benchmark test in February '96, NCAR personnel advised Cray Research that “there were no showstoppers.” The context of that remark is as follows:

a. The initial (November 30, 1996) BAFO from Cray Research included a new nonvector system that was the centerpiece of the offer and that was being designed. An elementary analysis of the machine's specifications showed that it would not meet the performance levels that Cray Research was projecting for our applications. This was a “show stopper” for that offer and we advised Cray Research of this. Cray Research verified our analysis and amended their BAFO by replacing this machine with other equipment.

b. The amended BAFO from Cray Research contained their T90 as the flagship system for the first two years of the proposal and the LTD was to be performed on it. Approximately two weeks before the February '96 LTD, Cray Research informed us that they could not perform the LTD on a T90 due to fundamental problems with the T90 memory system. This was another “showstopper” for the BAFO. Cray Research requested that they be allowed to perform the LTD on the C90. We agreed.

c) The May '96 system from Cray Research accounted for only about 10% of the total computing capacity in the BAFO.

Based on a) through c), UCAR concluded that FCC offered and demonstrated overwhelmingly superior technical performance and low risk relative to the Cray Research five-year offer. Thus, Cray Research lost this procurement because their BAFO had unacceptable technical risk-in particular, neither the September '96 nor any of the August '98 systems could be tested. In fact-and as noted in [2]-had FCC withdrawn from the competition, UCAR would have selected the three-year offer from Cray Research due to the risks of their five-year offer.[4]

If An Antidumping Order is Issued

UCAR and the community it serves currently enjoy world leadership in several areas of atmospheric sciences research that depend on high performance computing. In order to maintain this leadership, UCAR must have computing capabilities that are comparable to peer organizations throughout the world. The most powerful computer that UCAR has today sustains 5 Gigaflops. Meteorological centers in Australia, Canada, England, and elsewhere are installing systems that by January '98 will sustain from 20–80 Gigaflops on a single application. This is four to sixteen times as much computing capability as UCAR has at present. Further, we estimate that those centers are acquiring this capability at an annual cost that does not exceed the annual expenditure that UCAR offered in this RFP.

If an antidumping order is issued, then UCAR has two options:

1. Switch to highly parallel, nonvector systems. As evident in the RFP, we have the option to switch to these systems. Several U.S. manufacturers market parallel, nonvector systems. By switching to this

So with an amended BAFO and the last minute change to perform the LTD on the C90, Cray Research finally made an offer that did not have any “showstoppers.” The remark did not mean that Cray Research had won the competition, rather it meant they had qualified.

[4] UCAR estimates that today-eighteen months after their BAFO-about 80% of the capacity offered by Cray Research is still not demonstrable.

technology-and the two are interchangeable-UCAR is assured a competitive marketplace from which to procure equipment. We have already noted that meteorological centers around the world are rapidly increasing their computational capability and doing so without an increase in cost. If an antidumping order is issued, then UCAR believes that the parallel, nonvector marketplace is our best hope for obtaining comparable amounts of computing per dollar. However, some time will be required to acquire and convert to the new systems.

2. Broaden our national and international collaborations to include access to high performance computing systems. The U.S. atmospheric sciences community routinely participates in national and international research projects and collaborations. When scientifically appropriate, these activities can occasionally include access to leading edge, high performance computers including computers in other countries. For technical reasons, this option is not a desirable way to compute. Moreover, this approach cannot be relied upon to meet UCAR's computing needs in a systematic manner that serves all of its users.

So with an amended BAFO and the last minute change to perform the LTD on the C90, Cray Research finally made an offer that did not have any "showstoppers." The remark did not mean that Cray Research had won the competition, rather it meant they had qualified.

Both of these options will impede UCAR's rate of scientific progress while at the same time UCAR's international peers are accelerating their rate of progress. This will have far reaching, negative consequences. UCAR, plus the U.S. community it serves, may forfeit their research leadership in advancing technology for weather forecasting and climate modeling.

Summary

1. Cray Research lost this procurement because of unacceptable technical risk in its BAFO.
2. An antidumping order will have far-reaching, negative impact on U.S. leadership in atmospheric science.

Bibliography

1. "Accommodations Made for the Competitors," Comments by the University Corporation for Atmospheric Research on the Antidumping Petition of Cray Research, Inc.," dated August 16,

1996 and addendum thereto dated August 23, 1996 (both documents were made available to the ITC).

2. Letter from Frank Schuchat, Holme Roberts & Owen LLP, to ValerieNewkirk, Office of Investigations, U.S. ITC, dated September 18, 1996 .